Intraoperative Navigation in Plastic Surgery with Augmented Reality: A Preclinical Validation Study

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Background: Augmented reality allows users to visualize and interact with digital images including three-dimensional holograms in the real world. This technology may have value intraoperatively by improving surgical decision-making and precision but relies on the ability to accurately align a hologram to a patient. This study aims to quantify the accuracy with which a hologram of soft tissue can be aligned to a patient and used to guide intervention.

Methods: A mannequin's face was marked in a standardized fashion with 14 incision patterns in red and nine reference points in blue. A three-dimensional photograph was then taken, converted into a hologram, and uploaded to HoloLens (Verto Studio LLC, San Diego, Calif.), a wearable augmented reality device. The red markings were then erased, leaving only the blue points. The hologram was then viewed through the HoloLens in augmented reality and aligned onto the mannequin. The user then traced the overlaid red markings present on the hologram. Three-dimensional photographs of the newly marked mannequin were then taken and compared with the baseline three-dimensional photographs of the mannequin for accuracy of the red markings. This process was repeated for 15 trials ($n = 15$).

Results: The accuracy of the augmented reality-guided intervention, when considering all trials, was 1.35 ± 0.24 mm. Markings that were positioned laterally on the face were significantly more difficult to reproduce than those centered around the facial midline.

Conclusions: Holographic markings can be accurately translated onto a mannequin with an average error of less than 1.4 mm. These data support the notion that augmented reality navigation may be practical and reliable for clinical integration in plastic surgery. (*Plast. Reconstr. Surg.* 149: 573e, 2022.)

Augmented reality integrates a virtual and true environment, allowing users to interact with virtual elements (i.e., holograms) within the real world. Augmented reality devices provide surgeons with the ability to visualize a wide range of information, including two-dimensional photographs and three-dimensional holograms, in the operating room (Table 1). Our group has previously reported the potential of augmented reality to assist in soft-tissue planning and the integration of augmented reality headsets in the operating room.[1,2] Since this initial description, further studies have described the utility of the HoloLens (Verto Studio LLC, San Diego, Calif.) as an intraoperative tool for referencing virtual three-dimensional models of patient anatomy.[3–7]

After our initial experience using projected three-dimensional images to guide facial fat grafting intraoperatively, our group recognized the

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Table 1. Review of Commercially Available Augmented Reality Devices

	Manufacturer	Tethered vs. Untethered	Sterile User Interface	Positional Head and Hand Tracking	Computing Power	Battery Life	Developer Community Size and Resources	Cost	Other
HoloLens	Microsoft Inc.	Untethered	Yes: voice + hand	6 DOT head and hand	2GB RAM plus in-house GPU	2–3 hr	Extensive	\$3,000	Most developer resource; tinted visor
Magic Leap One	Magic Leap	Untethered	Yes: voice + hand	6 DOT head and hand	8GB RAM plus in-house GPU	2–3 hr	Growing	\$3,000	Newer developer community; tinted visor
ODG-R-9	Osterhaut Design Group	Untethered	No, touch sensor	6 DOT for head not hand	6GB RAM	4 hr	Limited	\$1,800	No depth sensor
Optinvent Ora 2	Optinvent	Untethered	No, touch sensor	No, needs add-ons	Smartphone powered	5 hr	Limited	\$800	Nonsterile
Meta 2	Meta	Tethered	Yes, voice + hand	6 DOT head and hand	Tethered computer Source	Unlimited	Limited	\$1,500	Tethered
Sony SmartEye	Sony Inc.	Tethered	No, touch sensor	No	Smartphone powered	1–2 hr	Limited	\$700	Tethered, nonsterile
Dream Glass	Dream World	Tethered	Yes, hand	No	Tethered source	Unlimited	Limited	\$400	Tethered, limited head tracking

DOT, degree of training; RAM, random access memory; GPU, graphics processing unit.

importance of registration and overlay of holograms onto a patient to aid intraoperative surgical decision making.[1-3] Methods for manually aligning a hologram onto a patient have been described, but few have investigated how accurately they can be achieved and whether these alignments can be used to guide a precise intervention.[8] Of those studies that have looked at the accuracy of augmented-reality guided interventions, the majority focus on either internal or bony anatomy, with little consideration being given to soft-tissue or surface topography. Given the rapid development of augmented reality technology and its potential use in plastic surgery, the purpose of this study was to investigate the accuracy with which a hologram can be aligned to the facial topography to guide soft-tissue procedures.

METHODS

Production and Visualization of Baseline Hologram

A standardized set of markings were placed on a female mannequin that included 14 facial incision patterns and injection points in red and nine reference points in blue. (**See Figure, Supplemental Digital Content 1**, which shows a three-dimensional image of the mannequin with both red and blue markings. This three-dimensional image was used to produce the hologram, ***http://links.lww.com/PRS/E927***.) Blue reference points were positioned at the following key facial anatomical landmarks: glabella, left and right medial and lateral canthi, left and right oral commissures, Cupid's bow, and the midsection of the vermillion border on the lower lip. Scandy Pro (Scandy LLC, New Orleans, La.) was used to take a three-dimensional photograph of the marked mannequin. The resulting three-dimensional image was then converted to a hologram from Alias Wavefront Object (.obj) to Filmbox (.fbx) format using Blender software (Blender Foundation, Amsterdam, The Netherlands). The hologram was uploaded through Verto Studio so it could be accessed on the HoloLens. (**See Figure, Supplemental Digital Content 2**, which shows a side-by-side view of the real mannequin after erasure of the red points and the hologram to the right side. The hologram was aligned to the mannequin using the blue points as references and the red markings were later redrawn by hand, ***http://links.lww.com/PRS/E928***.)

Method for Holographic Alignment

To assess the quality of the overlay between the hologram and the mannequin, the red markings were then erased from the mannequin surface but were preserved on the hologram. The hologram was manually overlaid onto the mannequin by referencing the blue markings. Verto Studio augmented reality software was used to improve alignment accuracy. Using the software, motion of the hologram is restricted to one plane per hand gesture. The following steps were used during each trial to standardize the alignment process:

1. Frontal alignment: To achieve alignment of the hologram onto the patient in the frontal perspective, manual movements were performed in the x and y planes. The quality of overlay from the frontal view was assessed via alignment of the blue markings. [**See Figure, Supplemental Digital Content 3**, which shows a user performing alignment of the hologram to the mannequin from a frontal perspective by translating the hologram in the x axis (*red arrows*) and y axis (*green arrows*) only. The right image shows the point of view of the user, ***http://links.lww.com/PRS/E929***.]
2. Profile alignment: Once frontal alignment was confirmed, the mannequin was rotated 90 degrees for a profile viewpoint. Incremental translational movements in the z axis were then performed. The accuracy of the profile alignment was assessed based on the agreement between the lateral profile of the real and holographic mannequins. [**See Figure, Supplemental Digital Content 4**, which shows a user performing alignment of the hologram to the mannequin from a lateral/profile perspective by translating the hologram in the y axis (*green arrows*) and z axis (*blue arrows*) only. The right image shows the point of view of the user, ***http://links.lww.com/PRS/E930***.]
3. Revision: After alignment in the profile view, frontal alignment was reassessed. If deemed accurate, the position of the holographic mannequin was fixed in place. If deemed suboptimal, the holographic mannequin was readjusted in the x-y plane to achieve a precise final alignment.

Method for Augmented Reality-Based Navigation

After ensuring proper overlay of the hologram onto the mannequin, the user wore the HoloLens to visualize the hologram and retrace the red markings. (**See Figure, Supplemental Digital Content 5**, which shows a user marking the mannequin based on the position of the overlaid red points. The image on the right shows the point of view of the user, ***http://links.lww.com/PRS/E931***.) Brightness was lowered on the augmented reality so that both the hologram and the real mannequin could be adequately visualized. No adjustments to the position of the hologram were made after initial alignment. The hologram was then removed, and a three-dimensional photograph was taken of the mannequin with the new red markings after each trial. The red markings were erased between each trial. This process was repeated for a total of 15 trials ($n = 15$).

Three-Dimensional Analysis of Markings

The baseline three-dimensional image of the mannequin and three-dimensional photographs taken after each trial were imported in .obj format and analyzed using Vectra Analysis Module software (Canfield Scientific, Inc., Parsippany, N.J.). The red markings changed after each trial, but the blue reference markings stayed constant. After completion of each trial, 32 ($n = 32$) surface distances were measured using three-dimensional software between prespecified landmarks on the red markings to the center of the unchanging blue markings. The distances calculated for each trial were compared to those initially measured on the baseline model. Once all 32 landmark pairs were measured and the difference from the baseline measurements was calculated, a total deviation value was calculated for the trial by taking the average of the absolute differences for all 32 measurements. (Figs. 1 and 2).

Statistical Analysis

Statistical analysis was performed using Microsoft Excel (Microsoft, Inc., Redmond, Wash.). Analysis of variance testing was performed to investigate the presence of significant differences between landmark pairs across all trials. Significance was set a priori at less than 0.05 for all analyses.

RESULTS

The mean difference between the baseline and trial measurements for all markings was 1.35 ± 0.24 mm, with a range of 1.08 to 1.65 mm (Table 2). There were no significant differences in the average accuracy between trials ($p = .56$). Analysis of variance testing revealed that red markings closest to the blue reference points were most likely to be accurately placed (red-blue

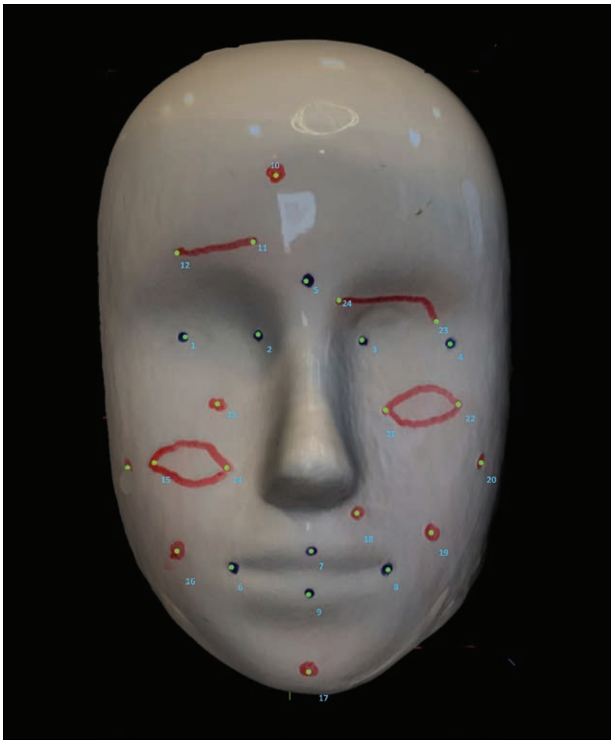

Fig. 1. Three-dimensional points were defined using computer software in order to establish the position of the markings that were drawn in augmented reality.

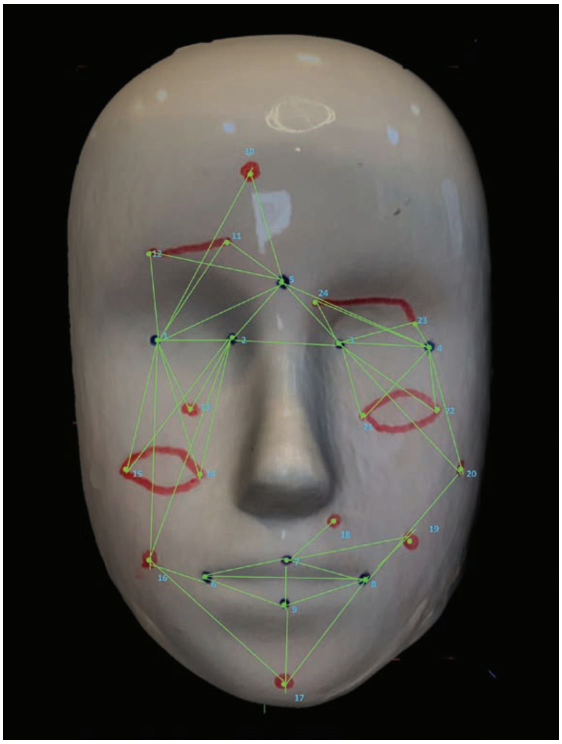

Fig. 2. The distances between specific points were mapped and calculated (*green lines*) and these values were compared between trials to determine the accuracy of the intervention.

landmark distance between 10 to 20 mm resulted in average accuracy of 1.01 mm versus accuracy of 1.18, 1.44 for 20 to 30 mm and 30 to 40 mm landmark distances, respectively, $p < 0.05$). This translated into markings on the lateral cheeks being the least accurate and markings near the brow, chin, and orbital regions being the most accurate. Table 3 demonstrates the relationship between the accuracy of markings and the distance of each marking to its closest blue reference point.

DISCUSSION

The current study demonstrates that a manually aligned hologram can guide an intervention with accuracy of 1.35 mm. Although augmented reality is a growing area in plastic surgery, few studies have objectively analyzed the accuracy of applied augmented reality technology to facial procedures and soft-tissue anatomy. Among the few studies that have investigated this, several automated methods for aligning holograms to patients have been investigated. Pepe et al. compared the use of external trackers to computer vision technology for automated alignment and found both methods to be lacking, with a discrepancy ranging from 3 to 9 mm.[9] In the past, our group has experimented with a variety of these methods for automated registration, including the use of quick response codes and computer vision alignment tools, but found these tools to be lacking, similar to the findings of Pepe et al. At present, manual registration through a stepwise process remains the most reliable and reproducible method and, therefore, was pursued in this study. Nonetheless, for this technology to be implemented in the most efficient manner in the operating room, an automated method of alignment may be ideal. Manufacturers of augmented reality devices have demonstrated interest in improving computer vision and the Microsoft HoloLens 2 (Verto Studio LLC), released in February of 2019. Computer vision refers to the ability of a video camera system and computer to parse through visual elements of an image and identify features using machine learning (i.e., the ability to identify eyes, nose, mouth, and other features on an image of a face). This technology is currently available to a limited degree on the HoloLens 1 and allows for automation of holograms on a face. The HoloLens 2 will feature improved target tracking and a dedicated onboard artificial intelligence chip that is dedicated to computer vision processing and can be used for this purpose.[10]

Table 2. Summary of Study Results (in mm) by Experiment

	Mean Error	SD	Median	Minimum	Maximum
Experiment 1	1.23	0.82	1.27	0.05	3.41
Experiment 2	1.43	1.59	0.94	0.09	5.88
Experiment 3	1.37	0.92	1.31	0.01	4.33
Experiment 4	1.27	0.97	1.04	0.09	3.66
Experiment 5	1.15	0.86	1.16	0.03	2.94
Experiment 6	1.51	1.44	1.28	0.03	5.28
Experiment 7	1.10	0.84	0.89	0.01	3.33
Experiment 8	1.08	0.66	0.90	0.03	2.87
Experiment 9	1.31	0.74	1.13	0.04	3.27
Experiment 10	1.51	1.09	1.11	0.08	3.72
Experiment 11	1.44	0.75	1.43	0.15	3.12
Experiment 12	1.10	1.19	0.79	0.04	5.32
Experiment 13	1.85	1.16	1.62	0.30	4.84
Experiment 14	1.10	1.10	0.82	0.01	4.70
Experiment 15	1.11	0.99	0.83	0.23	4.70
Total	1.30	1.01	1.10	0.08	4.09

The present study found that interventions (i.e., reproducing red markings) that were made further away from the reference points (i.e., blue markings) were performed less accurately than interventions performed closer to the reference points. The authors' explanation for this is that reference points give the user an opportunity to visually relate the position of the overlaid hologram on the real mannequin and, therefore, make real-time adjustments to the location of the intervention. For example, when the user is reproducing a red marking on the mannequin in an area that is close to a blue reference point, they can visualize relative inaccuracies in the alignment of the hologram and the mannequin by comparing the locations of the holographic and real reference points that should ideally be in the same place. If, for example, a holographic blue reference point is positioned slightly inferior to the corresponding reference point on the real mannequin, it would indicate the total hologram is aligned slightly inferior to its ideal position. To compensate for this, the user would perform the actual intervention (i.e., placing a red marking) slightly superior to the position of the holographic red marking on the mannequin. This corrective process becomes harder to accomplish when the red marking is further away from the reference points.

Table 3. Results of Analysis of Variance Analysis of Landmark Pairs*

Landmark Pair Distance	Count	Average Accuracy (mm)	Variance
10–20 mm	83	1.018019277	0.542361791
20–30 mm	153	1.180235294	0.609353576
30–40 mm	84	1.445857143	1.21938622
>40 mm	112	1.984625	2.573884363

*The distance between the red marking and blue reference point significantly impacted accuracy. When considering all measurements in the study, greater distance between red and blue marking resulted in a reduction in accuracy. This translated in areas of the face with the lowest density of blue points (i.e., lateral face and cheeks) being the least accurate.

Clinically, surgeons using augmented reality to guide soft-tissue intervention can utilize this information in two ways. First, as in the present study, artificial reference points can be marked on the patient before the generation of the three-dimensional model used for a hologram. By doing this, the surgeon can relate reference points on the hologram to real reference points on the patient and make precise real-time adjustments to the location of the intervention in a similar fashion to the technique described above.

It is likely that unique topographic details of the face also serve as natural references between the hologram and patient and provide the surgeon with the ability to adjust the location of an intervention on the face in real time. These innate references, including the nose, medial canthi, and mouth, are typically centered around the facial midline. In the present study, the interventions that were performed most accurately were also centered around the midline of the face, and the least accurate interventions were located on periphery of the face, supporting this concept. It follows that procedures that are centered around the facial midline (e.g., rhinoplasty, central facial fat augmentation, and procedures involving the lips and chin) may be more amenable to augmented reality navigation and produce more accurate interventions. Procedures that may be more challenging to apply augmented reality navigation to would, therefore, be located more peripherally on the face and might include face lift incision planning and procedures involving the mandible and the lateral cheek.

At present, three-dimensional technology and augmented reality navigation have been applied to surgical procedures involving bone, with little attention paid to soft tissue. The nondeforming nature of bone improves the ease of alignment compared to soft tissue, and studies involving bone are likely, therefore, viewed as more practical and pursued. To address this, the authors propose several theoretical techniques that may minimize the impact of soft-tissue deformation on the accuracy of augmented reality-guided intervention. First, when capturing three-dimensional topographic data of the patient that will be converted into a hologram, the patient should be positioned in the same position that they will be in when the procedure is performed. For most surgeries, this will be the supine position. By capturing the patient in the supine position, soft-tissue deformation via the effects of gravity that are present during surgery will be accounted for in the topography of the hologram. In addition, the use of neurotoxins and local anesthesia before three-dimensional data capture and during surgery may also minimize discrepancies in soft-tissue topography between the hologram and actual patient. When these techniques are performed, the accuracy of augmented reality navigation in soft-tissue surgery may approach the accuracy of augmented reality navigation in bony surgery that has been reported in several studies and found to be accurate to approximately 1 mm.[11–14]

Augmented reality navigation is a technique that offers surgeons the ability to translate preoperative three-dimensional images into virtual plans in the operating room.[2,15–17] With respect to soft tissue, three-dimensional photography and simulation have been used for both reconstructive and cosmetic surgery. For example, three-dimensional surgical plans for patients with a hemifacial soft-tissue defect can be designed by mirroring the anatomically normal side of the face onto the defect side to construct a color map indicating precise volumetric deficiencies on the affected side and can serve to guide autologous fat grafting. Similarly, three-dimensionally modeled cosmetic soft-tissue procedures can be designed using three-dimensional photography and applied software and carried forward into the operating room using two-dimensional images showing volumetric calculations or three-dimensional printed models. With respect to bony surgery of the face, there have been many studies reporting the value of three-dimensional planning for free-fibula reconstruction of the mandible or maxilla, and these plans often involve the use of intraoperative three-dimensional technology.[18-20]

When compared to traditional three-dimensional printed models, cutting guides, and jigs that are also used for this purpose in the operating room, augmented reality navigation offers several distinct advantages. From an efficiency standpoint, most hospitals that utilize three-dimensional printed models intraoperatively must wait days to weeks for models to be printed and shipped to their facilities. For the select institutions that have in-house three-dimensional printers, it often takes several hours to print the model and several more hours for postprocessing and sterilization that may delay emergencies such as complex traumatic reconstruction. By comparison, augmented reality offers quicker implementation of three-dimensional holographic models into the operating room by eliminating need for production and shipping time and does not present sterilization issues.[1] From a financial perspective, the main costs associated with augmented reality navigation are the one-time costs associated with acquiring the hardware and hologram visualization software in addition to three-dimensional data acquisition, which may be accomplished through computed tomography/magnetic resonance imaging data or three-dimensional cameras. At present, the Microsoft HoloLens used in the present study costs approximately $2,000, and the software for data acquisition and visualization was free. By comparison, medical-grade three-dimensional printed models may range from several hundred dollars to thousands of dollars per model plus shipping and engineering costs. In-house, commercial-grade three-dimensional printers are typically in the range of hundreds of thousands of dollars.

Augmented reality navigation is not without its drawbacks, however, including an unstudied learning curve associated with using this technology, problems associated with these devices being early “first-generation” models, and the lack of tactile feedback in holographic guides and jigs when compared to traditional three-dimensionally printed alternatives. To date, there have been no formal studies investigating the learning curve associated with this technology. which is likely steep given an entirely new method for interfacing between the augmented reality device and headset (i.e., voice commands and hand gestures). Furthermore, the ability of surgeons to integrate relatively unfamiliar three-dimensional data packets into operating room without disrupting surgical workflow and efficiency may pose a challenge, and it is likely that some degree of prior training with the technology will be needed before it can be used confidently in a clinical setting. Future studies investigating this topic are of paramount importance. Is it probable that as these augmented reality devices improve from the current status of being first-generation models, the user experience will become simpler and more cohesive, and they will be more easily integrated into the clinical setting.

Whether augmented reality technology has a role to play in surgical simulation and resident training in addition to clinical utility is an open question. To date, much of the innovation in three-dimensional simulation for the training of residents has been focused on virtual reality because it offers a more controlled and immersive digital setting ideal for simulation, as opposed to augmented reality. Virtual reality has been shown in the orthopedic surgery literature to be an effective tool for teaching first-year residents core surgical procedures, including total knee and total hip replacement surgery.[21] Preliminary studies in other surgical disciplines, including neurosurgery and orthognathic surgery, have shown that augmented reality may also be used as a tool for teaching residents.[22–24] It is likely that there are potential roles for augmented reality for teaching core plastic surgery procedures as well, though at present there are no established virtual curriculums for this.

Augmented reality also bypasses the concern for sterility of printed models. Mitsuno et al. recently described the utilization of augmented reality in trauma reconstruction, where holograms of the patient preoperatively and simulated ideal postoperative results were immediately available in the operating room.[8] One disadvantage to augmented reality holograms is the lack of tactile feedback that is available in the three-dimensional printed model. Nevertheless, software engineers have made attempts to add tactile feedback to augmented reality navigation by integrating an augmented reality display with a robotic, haptic-feedback–enabled hardware. Lin et al. described the use of a haptic-feedback surgical saw for use in augmented reality–guided mandibular angle osteotomies on animal models.[11]

The present study identified an error margin of 1.35 mm when using augmented reality to guide the location of an intervention on the face. It is important to note that certain areas of the face that are involved in substantial animation and microexpression during three-dimensional capture or the surgery itself also require special attention. For example, the oral commissures and eyelids are susceptible to moving both during three-dimensional image capture and the procedure itself, potentially limiting the accuracy of augmented reality–guided interventions in these areas. Although introducing reference points that are adjacent to these challenging areas may improve the accuracy of augmented reality–guided intervention, it is likely that at this early stage of the technology, areas of the facial midline that are less susceptible to animation and microexpression, such as the nose, forehead, chin, and medial aspects of the mouth, will stand to benefit the most from augmented reality navigation.

The limitations of this study include the use of mannequins rather than clinical patients. In this early stage of investigation of augmented reality, a mannequin was chosen to limit variables such as motion during the augmented reality intervention and three-dimensional capture process and variability among facial proportions. In addition, to simplify the study, a single individual performed all interventions and user variability in the accuracy of augmented reality navigation was not investigated. Future studies should seek to assess the impact of scalable and standardized training modules on user variability and accuracy and will be needed before widespread adoption of this technology. Finally, Scandy Pro was chosen as the three-dimensional capture method of the mannequins because Vectra H1 (Canfield Scientific, Inc.) was not capable of stitching photographs of the mannequin into an accurate three-dimensional model. Nonetheless, Scandy Pro is an accurate tool for three-dimensional data acquisition and is comparable to Vectra H1.

CONCLUSIONS

Augmented reality offers an accurate and reproducible method for translating three-dimensional image-based virtual plans onto the true facial contour, with an accuracy of 1.35 mm. This technology can be expanded to other areas of plastic surgery, allowing for integration of various types of three-dimensional surgical plans for soft-tissue procedures in the operating room. In addition, augmented reality bypasses the consideration for processing, shipping, and sterility required for three-dimensionally printed models. This study demonstrates preliminary data needed to pursue augmented reality and three-dimensional technology as a reliable guide for soft-tissue facial procedures. The potential applications of augmented reality in plastic surgery are a topic of ongoing investigation.

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